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MOLECULAR CLOUDS AND GALACTIC SPIRAL STRUCTURE

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ABSTRACT

Two large-scale 2.6 mm CO surveys of the galactic plane, one in the first quadrant ($l = 12°$ to $60°$, $b = -1°$ to $+1°$), the other in the second ($l = 105°$ to $139°$, $b = -3°$ to $+3°$), have provided evidence that, contrary to previous findings, molecular clouds constitute a highly specific tracer of spiral structure. Molecular counterparts of five of the classical 21 cm spiral arms have been identified: the Perseus arm, the local arm (including Lindblad's local expanding ring), the Sagittarius arm, the Scutum arm, and the 4-kpc arm. The region between the local arm and the Perseus arm is apparently devoid of molecular clouds, and the interarm regions of the inner Galaxy appear largely so. CO spiral structure implies that the mean lifetime of molecular clouds cannot be greater than 1×10^8 years, the time required for interstellar matter to cross a spiral arm. Conservation of mass then sets a limit on the fraction of the interstellar medium in the form of molecular clouds: it cannot exceed one-half at any distance from the galactic center in the range 4–12 kpc.

Subject headings: galaxies: Milky Way — galaxies: structure — interstellar: molecules

I. INTRODUCTION

Do molecular clouds constitute a good tracer of spiral structure? To settle this controversial question we have undertaken two CO surveys, one a wide-angle study of the Perseus arm, the other a closely sampled survey of the inner galactic arms in the first quadrant. Previous CO surveys have suffered from two limitations: they were largely confined to the first quadrant, and they were severely undersampled. On the question of spiral structure they have yielded contradictory verdicts. According to Burton and Gordon (1978), "clearly there is some higher-order arrangement of dark clouds within the Galaxy, be it simple clustering or a large-scale design such as spiral structure." Scoville, Solomon, and Sanders (1979), however, assert, "it is clear from the absence of a recognizable spiral form . . . that most of the clouds cannot be situated within a regular pattern of spiral arms." If spiral structure is absent in CO, molecular clouds may be old objects existing much longer than the time required for interstellar matter to cross a spiral arm (Scoville and Hersh 1979).

Our new surveys show that a "higher order arrangement" does exist in CO, and that molecular clouds are in fact an excellent tracer of spiral structure. Both surveys were made with a 1.2 m telescope in New York City during the colder months of 1978 and 1979 when the opacity of atmospheric water vapor was low. The telescope's antenna, a scaled-down standard radio Cassegrain, has a beamwidth of 7.′5 at 115 GHz, the frequency of the fundamental rotational transition of CO. Its detection system consisted of a superheterodyne receiver whose double sideband noise temperature was typically 420 K, followed by a filter bank spectrometer with 256 filters, each 250 kHz wide; at 115 GHz this provides a resolution in radial velocity of 0.65 km s^{-1}, and a spectral range of 166 km s^{-1}. (Spectra, however, were generally smoothed to a resolution of 1.3 km s^{-1}.) Position switching was used to flatten the instrument's spectral response. The telescope can be switched from a given point in the sky to another several degrees away in less than 1 s, permitting a rapid 30 s switching cycle; spectral baselines as a result are extremely flat.

II. PERSEUS ARM SURVEY

In the direction of the Perseus arm we have surveyed a slightly irregular band along the galactic plane about 6° wide and 34° long, from $l = 105°$ to $l = 139°$. Two different sampling procedures have been followed: below $l = 128°$ observations were made every four beamwidths (0.°5) in l and b, while above 128° observations where made every beamwidth in l and b and then smoothed to an angular resolution of 0.°5. The integration time per unit solid angle in either case was about the same (1 hour per square degree), so the smoothed spectra above 128° have approximately the same signal-to-noise ratio as those below. In addition, however, many molecular clouds discovered below 128° were observed every beamwidth or every other beamwidth, as much as 10 hours per square degree being devoted to such fine-scale mapping. As a result the survey is more sensitive to small molecular clouds below 128° than above, but is otherwise unbiased.

Figure 1 is a conventional longitude-velocity (l, v) diagram obtained by integrating the survey across the galactic plane. The local arm is the prominent lane of CO clouds lying approximately in the velocity interval 0 to -20 km s^{-1}, and the Perseus arm is the fainter parallel lane at -40 to -60 km s^{-1}. As the arrows at the top and bottom of the figure show, these molecular arms lie close to the respective 21 cm arms. There is even some evidence in the local molecular arm for the 21 cm subdivision which Lindblad *et al.* (1973) have interpreted as an expanding local ring of gas possibly associated with Gould's belt.

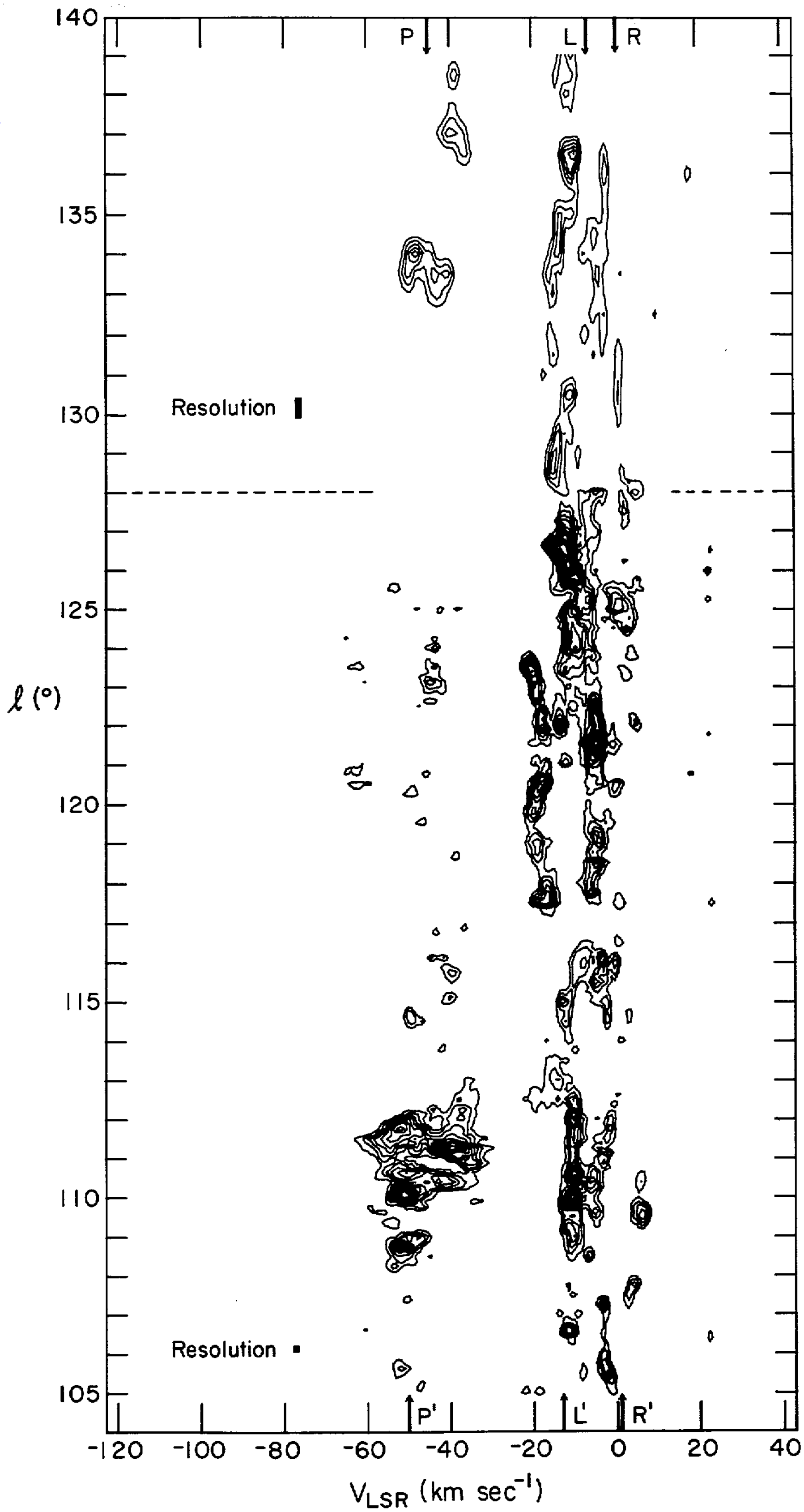

FIG. 1.—Longitude-velocity diagram obtained by integrating the Perseus arm CO survey across the galactic plane. Contours denote equal values of $\int T_R\,db$, where T_R is antenna temperature corrected for atmospheric absorption and beam efficiency, and b is galactic latitude; the contour interval is 0.5 K-arcdegree. Above $l = 128°$, spectra were taken rapidly, and the survey has been smoothed to a longitude resolution of 0°5 to enhance the signal-to-noise ratio. Arrows at top and bottom of the figure denote the ridges of peak 21 cm emission (almost straight lines over the region of the diagram) from the Maryland—Green Bank Survey (Westerhout 1973): PP′ is the Perseus arm, LL′ the local arm, RR′ Lindblad's local expanding ring. The large object in the Perseus arm at $l = 134°$ is the molecular complex associated with W3 (Lada *et al.* 1978); the even larger object at $l = 110°$ is a very big molecular complex associated with a number of H II regions and possibly the supernova remnant Cas A.

The total absence of CO emission in the classical interarm region—the vertical empty lane in Figure 1 from approximately -20 to -40 km s^{-1}—is perhaps the most important finding of the Perseus arm survey. This gap does not necessarily mean that molecular gas is nonexistent in the interarm region—such gas could be so cold, or diffuse, or in such small clumps as to escape detection. It does imply that molecular clouds as commonly defined by CO observations—objects larger than 5 pc with CO temperatures greater than 1–2 K—do not exist between the arms, or are extremely rare.

Simply by counting molecular clouds in Figure 1 we find that the number in the interarm region is at least a factor of 10 lower than that in the Perseus arm. This limit can be translated into relative densities per unit area projected on the galactic plane by assuming that the observed clouds uniformly fill the Perseus arm as defined either by OB stars (Humphreys 1979), or by the kinematic distances of the molecular clouds themselves. Both methods yield the same result: between $l = 105°$ and $l = 139°$ the Perseus arm covers an area of about 2 kpc^2, and the interarm region about 1 kpc^2, so the area ratio is 2. We conclude that the mean projected density of molecular clouds in the interarm region is at least a factor of 5 lower than that within the Perseus arm.

III. FIRST QUADRANT SURVEY

Is the region covered by our Perseus arm data typical of the Galaxy as a whole? Our CO survey of the first quadrant suggests that it is. This survey covers a uniform band 2° wide centered on the galactic equator, extending from $l = 12°$ to $l = 60°$. An inner strip 0°.5 wide has been sampled every beamwidth in l and b, the rest every two beamwidths. The survey comprises a total of over 3000 CO spectra, each representing typically 8 minutes of observation. In a typical spectrum at a velocity resolution of 1.3 km s^{-1} the rms noise was 0.3 K, which is comparable to that of previous CO surveys.

Figure 2 (Plate L2) is a gray-scale representation of the (l, v) diagram obtained when this first quadrant survey is integrated over b. As the insert in the diagram shows, it is possible to identify molecular counterparts of all the classical 21 cm arms of the inner Galaxy. The intense vertical lane of CO near 5 km s^{-1}—A and B in the insert—is again Lindblad's local ring, a continuation of the feature seen toward the Perseus arm; the Sagittarius arm is the nearly vertical loop C; the Scutum and 4-kpc arms are the two pronounced arcs D and E toward the bottom of the diagram. As toward the Perseus arm, interarm regions appear free or largely free of molecular clouds: note in particular the large lane between Lindblad's feature and the Sagittarius arm, the hole within the loop of the Sagittarius arm, the hole between the Sagittarius and Scutum arms, and the hole between the Scutum and the 4-kpc arms.

The most important exception to the straightforward pattern of spiral arms in Figure 2 is the apparent bridge of CO emission between the Sagittarius and Scutum arms near the terminal velocity curve at 85 km s^{-1} (between C and D). This might seem to be evidence for a population of weak interarm clouds made visible by the velocity crowding near the terminal velocity. That this is not in fact the correct explanation is proved by the failure of the bridge to extend fully to the terminal velocity curve (note the notch at $l = 36°$), its high intensity relative to the adjacent interarm hole, and its sharp low-velocity edge. A galactic spur at precisely this location has long been postulated by 21 cm observers (Weaver 1970; Shane 1972); the CO bridge is simply the molecular counterpart. Without this spur, the spiral structure of the inner Galaxy would be much more apparent, and its presence is probably one of the main reasons why spiral structure largely escaped notice in previous CO surveys.

It is instructive to compare Figure 2 with the Berkeley Low-Latitude Survey of Neutral Hydrogen, from which fairly comparable (l, v) diagrams have been prepared; the agreement with the diagrams derived from the most intense 21 cm features is particularly striking (Weaver 1974, especially their Fig. 3). There is a detailed match of the CO and 21 cm arms, interarm regions, and terminal velocity curves, with the CO features being on the whole slightly better defined and of higher contrast. From this comparison it is clear that CO is at least as specific a tracer of spiral arms as the 21 cm line.

Similar conclusions regarding the relationship between molecular clouds, spiral arms, and neutral hydrogen have been drawn by Stark (1979) from his CO observations of M31. The CO emission from the two

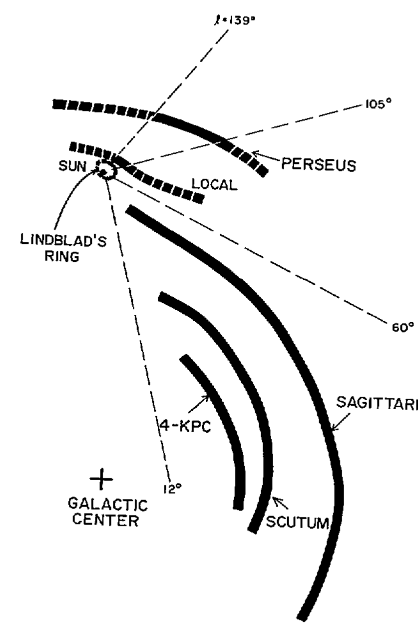

FIG. 3.—21 cm spiral arms which have been identified in the present CO surveys. Location of the arms in projection on the galactic plane has been adapted from the analyses of Simonson (1976), Lindblad *et al.* (1973), Burton and Shane (1970), and Shane (1972).

prominent arms on the NW minor axis of M31 is over 3 times more intense than the interarm emission, and as we find in our own Galaxy, the large-scale CO distribution is remarkably similar to that of neutral hydrogen.

Brief comparison of our first quadrant survey with previous CO work is appropriate. One might wonder how it is possible with a small telescope to detect galactic structure that eluded detection with larger instruments. The answer is that a large telescope is of no particular advantage when searching for wide-angle objects, and can become a liability if, as a consequence of the small antenna beam, the observer is forced severely to undersample the sky. This was the procedure followed in the previous CO surveys, where a large area was mapped but a much smaller area was actually observed. Burton and Gordon (1978) observed a total area of only 0.15 deg^2, and Solomon and Sanders (1979) an area of only 0.25 deg^2; by contrast, we observed an area of 50 deg^2. In previous CO (l, v) diagrams there are hints of the main galactic features which we have identified in Figure 2—Lindblad's local ring, for example, is rather distinct in Figure 1 of Burton and Gordon (1978) and Figure 13 of Solomon and Sanders (1979). Because of the undersampling, however, the more important and subtle distant arms and interarm regions of the Galaxy were so indistinct as to escape notice.

Finally, by adopting the analysis of various 21 cm workers, we show in Figure 3 the molecular arms of the Galaxy in projection on the galactic plane. Since molecular clouds are a highly specific tracer of galactic structure, it should prove possible with CO observations to improve our knowledge of the large-scale structure of the Galaxy, but this remains to be done. We expect on the basis of experience with the 21 cm line that progress will require extensive CO observations in the fourth quadrant from the southern hemisphere.

IV. DISCUSSION

The existence of CO spiral structure implies that molecular clouds are not long-lived galactic objects. They are formed, our data suggest, when interstellar gas enters a spiral arm, and are largely destroyed or modified by the time they leave. Several mechanisms have been suggested for the disruption of molecular clouds, including expanding H II regions, stellar winds, supernova explosions, and radiation pressure from OB associations. Whether on leaving an arm molecular clouds largely revert to atomic and ionized gas, or remain molecular in small clumps or at sufficiently low density and temperature to escape detection, we cannot say. Our observations show merely that little of the interarm gas is concentrated into molecular clouds of the kind found in spiral arms.

An upper limit for the lifetime of molecular clouds is the time required for a parcel of interstellar gas to cross a spiral arm. According to the density wave theory of spiral structure this is about 1×10^8 years (Roberts 1969), and that is the value which we will tentatively adopt as an upper limit for the mean lifetime of molecular clouds. Since open clusters and OB subassociations seem largely to dissipate their parental molecular clouds after only 3×10^7 years (Bash, Green, and Peters 1977; Kutner *et al.* 1977), we suspect that 1×10^8 years represents a conservative upper limit.

Finally, if molecular clouds are essentially transient objects, they cannot by conservation of mass represent the dominant component of the interstellar medium. Half the time as it circles the Galaxy, material in a given molecular cloud must exist in some other form. A rough equipartition of mass between molecular clouds and H I is, however, permitted, and this alternative in our view offers the best reconciliation of the important observational constraints. In particular, equipartition is consistent both with the galactic γ-ray data (Stecker *et al.* 1975), which imply that a large fraction of the interstellar gas in the inner galaxy is molecular, and also with the present CO surveys, which imply that this fraction is unlikely to exceed one-half by very much.

Fuller descriptions of the two surveys discussed here, including a catalog of the first quadrant CO spectra, are being published separately. We wish to thank D. Kerner and J. Montani for help with the observations, and A. Smith for assistance with the data analysis.

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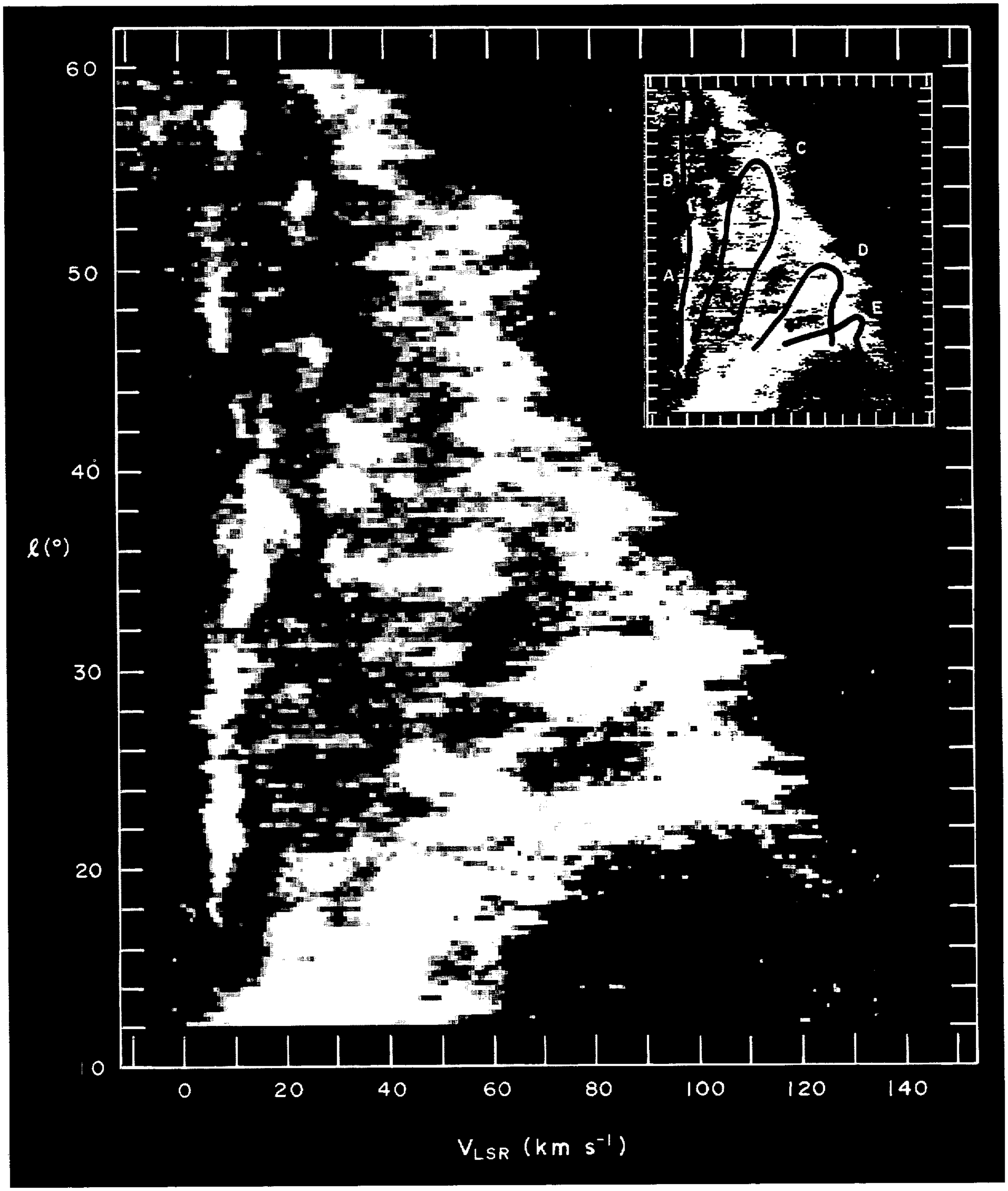

FIG. 2.—The longitude-velocity diagram obtained when our first quadrant CO survey is integrated across the galactic plane from $b = -1°$ to $+1°$, and smoothed by 0.25° (two beamwidths) in l. The most intense areas of emission correspond to integrated intensities of more than 30 K-arcdegrees. The insert locates the main 21 cm arms with respect to the CO (l, v)-diagram. A and B are Lindblad's local ring, according to the 21 cm analyses of, respectively, Burton and Shane (1970), and Lindblad *et al.* (1973); C is the Sagittarius arm, according to Burton and Shane (1970); D and E are, respectively, the Scutum and 4-kpc arms, according to Shane (1972).

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